A LOOK AT SCALING OF GROUND MOTION WITH MAGNITUDE FROM INTRASLAB EARTHQUAKES

R.J. Archuleta\textsuperscript{1} and C. Ji\textsuperscript{2}

ABSTRACT

We computed synthetic three-component accelerograms up to 10 Hz for intraslab earthquakes with moment magnitude $M$ 6.2, 6.8, 7.4 and 8.0. We simulated intraslab earthquakes for the Japan Trench and for Cascadia using a 1D velocity and attenuation model representative of the structure. For Japan, the center of the fault is at 70 km depth; for Cascadia, 55 km. We considered two orientations of finite faults embedded within the subducted plate: high-angle normal fault at 73\degree\, and a low-angle at 17\degree. For each orientation, we considered a heterogeneous slip distribution with five hypocenters. For each orientation and for each hypocenter we used the UCSB broadband method to compute accelerograms for 85 sites at distances up to 256 km. The age and temperature (600\degree\,C) of the subducted plate place limits on the maximum width of the fault: Japan, 55 km; Cascadia, 15 km. We find that both PGA and PGV decay with distance $\sim 1/R^2$, which is partly due to attenuation. However, even for a halfspace with no attenuation, the decay with distance is greater than $1/R$. We find magnitude saturation for intraslab earthquakes in Cascadia, but no magnitude saturation for the Japan Trench. The magnitude saturation results from the smaller maximum width (15 km) of the Juan de Fuca subducted plate in Cascadia compared to a maximum width (55 km) for the subducted Pacific Plate in the Japan Trench.

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A Look at Scaling of Ground Motion with Magnitude from Intraslab Earthquakes

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\section*{ABSTRACT}

We computed synthetic three-component accelerograms up to 10 Hz for intraslab earthquakes with moment magnitude $M$ 6.2, 6.8, 7.4 and 8.0. We simulated intraslab earthquakes for the Japan Trench and for Cascadia using a 1D velocity and attenuation model representative of the structure. For Japan, the center of the fault is at 70 km depth; for Cascadia, 55 km. We considered two orientations of finite faults embedded within the subducted plate: high-angle normal fault at 73° and a low-angle at 17°. For each orientation, we considered a heterogeneous slip distribution with five hypocenters. For each orientation and for each hypocenter we used the UCSB broadband method to compute accelerograms for 85 sites at distances up to 256 km. The age and temperature (600°C) of the subducted plate place limits on the maximum width of the fault: Japan, 48 km; Cascadia, 15 km. We find that both PGA and PGV decay with distance $\sim 1/R^2$, which is partly due to attenuation. However, even for a halfspace with no attenuation, the decay with distance is greater than $1/R$. We find magnitude saturation for intraslab earthquakes in Cascadia, but no magnitude saturation for the Japan Trench. The magnitude saturation results from the smaller maximum width (15 km) of the Juan de Fuca subducted plate in Cascadia compared to a maximum width (48 km) for the subducted Pacific Plate in the Japan Trench.

\section*{Introduction}

Earthquakes with focal depth in depth range from 50 km to 300 km predominately represent the brittle failure within descending slabs (intra-slab [1]) and are categorized as intermediate depth intraslab earthquakes (IDIE’s) in seismology. Notable IDIE’s include $M_W$ 6.7 1965 Seattle,

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2001 Mw 6.8 Nisqually, 2008 Mw 6.9 Northern Iwate Japan, and the recent earthquakes in Mexico, Mw 8.1 Sept. 7 and Mw 7.1 Sept 19, 2017 etc. These earthquakes are less frequent. According to global CMT project (http://www.globalcmt.org), on average there is only one Mw>7.4 IDIE since 1976. However, large IDIEs present a significant seismic hazard. To evaluate their seismic hazard, the tectonic description of the subducted plate and its environment has to be considered. We assume that the large IDIEs occur on pre-existing faults [2, 3] that were formed before subduction. The widths of their rupture planes in old slab are further limited by serpentine dehydration [4, 5, 6] and stress stages due to plate unbending [7,8].

For this presentation, we consider two distinctly different subduction zones: Japan Trench where the Pacific Plate is being subducted beneath the northern part of Honshu and Cascadia where the Juan de Fuca Plate is being subducted off the northwest coast of the United States and southern most British Columbia. At the Japan Trench the Pacific Plate is about 130 Ma; for Cascadia, the Juan de Fuca Plate is about 6-9 Ma at the trench. They are then the representative scenarios of old and young subduction zones. Assuming the preexisting deformation of oceanic plate is limited to be shallower than 600° isothermal [9], we use the global compilation of age and temperature isotherms from [9] to estimate the maximum width of 55 km and 15 km of the subducted Pacific Plate and Juan de Fuca Plate, respectively. For old subduction zone, we adopt the hypothesis that the rupture occurs along the reactive outer-rise fault as the result of plate unbending [7, 8]. Further assuming the neutral plate in the middle of deformation zone and the outer-rise fault on average have a dip angle of 45°, the width of fault plane is then about 40 km.

Simulations

We fix the center of the finite fault at a particular depth: 70 km for Japan and 50 km for Cascadia. The focal mechanism has two possible fault orientations. We only consider a high-angle fault 73° and a low-angle fault 17°, with the angle measured relative to a plane parallel to the free surface. It is noteworthy that such focal mechanisms are consistent with the Global CMT solutions of the 2001 Mw 6.8 Nisqually earthquake and 2008 Mw 6.8 Northern Iwate earthquake (http://www.globalcmt.org). We assume a rectangular fault plane where the width (cutting across the subducted plate) and length (parallel to the trench) are computed for each magnitude assuming an average static stress drop of 10 MPa for intra-slab earthquakes. Extending the approach of Parsons and others [10] for strike-slip and dip slip earthquakes, we derived a simple empirical relationship between stress drop, seismic moment and fault length and width of a rectangular fault plane undergoing normal fault rupture.

$$\Delta \sigma = \frac{16}{3\pi} \frac{M_0}{W^2 L} \frac{W}{2.2 L}, \quad \frac{W}{L} \leq 1$$  \hspace{1cm} (1)

where $\Delta \sigma$ is stress drop, $M_0$ is seismic moment, $W$ is fault width and $L$ is fault length. For any given event, we first estimate its radius $r$ assuming a circular fault, $r = \left(\frac{2 M_0}{16 \Delta \sigma}\right)^{1/3}$. When $2r < W_{max}$, where $W_{max}$ is the maximum width allowed, we use $W = L = 2r$. When $2r > W_{max}$, we set $W = W_{max}$ and conduct a grid search for fault length $L$ that satisfies equation (1).
The UCSB broadband method [11] uses a heterogeneous slip distribution defined by a von Karman wavenumber spectrum. The corner of the von Karman spectrum depends on a correlation length. We have used both a fixed correlation length (6 km) and a magnitude-dependent correlation length [12]. Because the sites are so far from the fault, we found little difference in comparisons made for Cascadia. We assume that the rupture initiates at a given hypocenter and then propagates roughly radially along the fault. The slip and the other kinematic parameters—rise time, peak time (time for slip rate to reach its maximum), rupture velocity—are all correlated [11, 13]. The cumulative moment-rate function must have a spectrum that is close to an Aki-Brune [14,15] omega-square spectrum with a corner that corresponds to stress parameter of 5 MPa [16]. The slip and other kinematic parameters are iterated, while maintaining their correlation, until a suitable moment-rate function is found. An example of the slip distribution and rupture time for a M 8.0 simulation for Japan is shown in Fig. 1. Note that the apparent width is larger than 40 km because the UCSB broadband method tapers the slip to zero at the edges of the fault. The apparent large width (48 km) ensures that the full 40 km width contributes to the seismic moment.

![Figure 1. Example of heterogeneous slip distribution of von Karman spectrum k^2 with 6 km correlation. Stars with numbers indicate hypocenter locations used in simulations. Green lines show location of rupture front at times in seconds.](image)

On the fault plane, we place five hypocenters on imaginary lines that bisect the width and length; one hypocenter is at the center of the fault and the other four toward the edges of the fault. In this construction, we can capture directivity parallel to the length and up- and down-dip.

The fault is embedded in a 1D velocity/attenuation structure (Fig. 2). The Cascadia velocity structure has a noticeable low-velocity zone. Because the fault is below this low-velocity zone, the seismic waves will pass directly through. Except for the upper 4 km, the S-wave velocity structure for Japan and Cascadia are quite similar but the attenuation structure is noticeably different. The 1D Green’s functions are computed to 0–25 Hz.
Using a point at the earth’s surface directly above the center of the fault as (0,0), we placed concentric rings, each with 12 sites equally spaced in azimuth, at radial distances of 4, 8, 16, 32, 64, 128 and 256 km. One site is at (0,0) giving a total of 85 sites. We use the UCSB broadband method [11] to compute three components of ground acceleration. Each fault is subdivided into a grid of 0.1 km x 0.1 km squares. Theoretically, this limits the fidelity of the accelerograms at any azimuth to 10 Hz [17]. However, that is strictly true only for sites affected by backward directivity; accelerograms at sites at all other azimuths will have fidelity more like 20 Hz [17].

An earthquake that nucleates at hypocenter #8 (Fig. 1) would have a significant component of rupture updip as well as spreading along strike; while an earthquake that nucleates at #2 would have a significant component of downdip rupture. Nucleation at either #4 or #6 would result in ruptures that are primarily along strike.

**Results**

For Japan and Cascadia, we consider four moment magnitudes: 6.2, 6.8, 7.4 and 8.0. The rupture can occur on a fault with a high-dip angle (73˚) or a low-dip angle (17˚). We allow for five hypocenters relative to the fault as shown in Fig. 1. The slip distribution is different between the high- and low-angle faults. For a given dip angle and tectonic region the slip distribution is the same for each hypocenter. Of course, different slip distributions are used for Japan and Cascadia simulations. Considering three components for all sites, fault orientations, and hypocenters we computed 2550 accelerograms for both Japan and Cascadia.
In Fig. 3 we show seven, horizontal accelerograms (component is parallel to strike) that are distributed around the fault; all sites are 256 km from a point we label (0,0)—the projection of the center of the fault to the earth’s surface. The earthquake is a $M_7.4$ on a low-angle (17° dipping) fault plane. Hypocenter is at location # 4 (Fig. 1) on the fault plane; however, these accelerograms are for a different simulation. Because the epicenter is closest to site 80, one can see the progression of P and S waves first arriving at site 80 and arriving later at the other sites. Although site 74 is best aligned for forward directivity, the largest amplitude (~0.04 m/s/s) occurs at site 76. The fault size is small compared to the distance; the distribution of slip on the fault and radiation pattern are more important than directivity.

In Fig. 4 we show an example of PGA versus closest distance to the fault for a $M_7.4$, high-angle fault rupture. The PGA are color-coded to show results from ruptures that nucleate at locations #2, #5 and #8 (Fig. 1). The effect of directivity (compare PGA blue –downward directivity– with yellow –upward directivity) for sites in the epicentral region is clear.

Having computed the PGA and PGV for the various magnitudes and different fault orientations, we examined scaling with respect to magnitude. Because there are a wide range of distances closest to the fault we have gathered PGA’s over a range of distances. In Fig. 5 we show the scaling of PGA vs $M$ for distances 220-280 km. We have not computed ground motion for a $M_8.0$ in Cascadia. We consider the fault length unphysical: >800 km which results from the physical limits...
on the width (15 km) of the subducted Juan de Fuca plate. The basic result (Fig. 5) is that PGA (same for PGV) saturates with magnitude for Cascadia but does not saturate for Japan.

Figure 4. Geometric mean of the two horizontal components of PGA plotted versus closest distance to the fault for a high-angle rupture with M 7.4. This plot combines results from hypocenters S2, S5 and S8. Left is PGA for Japan Trench; right is Cascadia.

Figure 5. Natural log of the geometrical mean of PGA plotted versus magnitude in distance range of 220-280 km. It is clear that PGA is saturating for magnitude greater than 6.8 in Cascadia while it is not saturating for Japan.
Conclusions

We have simulated intraslab earthquakes for the Japan Trench and Cascadia. The intraslab earthquakes had magnitudes 6.2, 6.8, 7.4 and 8.0 (except Cascadia). We computed broadband accelerograms using the UCSB broadband method [11, 13]. Both PGA and PGV decay with distance Rrup (Rrup is closest distance to the fault) with a dependence that is greater than 1/Rrup but less than 1/Rrup^2. The PGA and PGV show magnitude saturation for Cascadia but no magnitude saturation for the Japan Trench. We attribute the magnitude saturation to the limited depth over which an intraslab earthquake can rupture in the subducted Juan de Fuca Plate. However, because the Pacific Plate being subducted in the Japan Trench is much older and hence much thicker, the width of the assumed fault plane is not limited for magnitudes less than 8.0.

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